Title
Effects of scleral-lens oxygen transmissibility on corneal thickness: A pilot study.

Journal
Contact lens & anterior eye : the journal of the British Contact Lens Association, 42(4)

ISSN
1367-0484

Authors
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et al.

Publication Date
2019-08-01

DOI
10.1016/j.clae.2019.04.002

Peer reviewed

Contact Lens and Anterior Eye xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Contact Lens and Anterior Eye

journal homepage: www.elsevier.com/locate/clae

Effects of scleral-lens oxygen transmissibility on corneal thickness: A pilot study

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ARTICLE INFO

Keywords:
Scleral lens
Oxygen transmissibility
Corneal edema
OCT

ABSTRACT

Purpose: To investigate the effect of various oxygen transmissibilities (Dk/t) of scleral lenses and corneal thickness recovery time from overnight eye closure with patching on corneal edema during 5 h lens wear.

Methods: Scleral lenses (hofocon A, 15.6 mm diameter) were worn bilaterally with three different Dks (100, 140, and 160 Barrer). Central and peripheral corneal thickness (CCT and PCT) were measured using optical coherence tomography. Four subjects were randomly selected for one additional visit and asked to patch one eye before night sleeping. The patch was not removed until lens insertion to avoid corneal deswelling. Then CCT of both eyes was measured.

Results: Ten neophytes with healthy eyes participated in the study. Mean [95% CI] Dk/t of the study lenses was 32.0 [29.2, 34.7] hBarrer/cm. Mean [95% CI] CCT immediately upon lens insertion and after 5 h of lens wear were 532.4 [520.3, 544.5] μm and 538.7 [526.5, 551.0] μm, respectively. Mean [95% CI] percentage change (%Δ) in CCT was 1.2% [0.9%, 1.5%], 1.2% [0.9%, 1.4%], and 0.8% [0.6%, 1.1%] for CCT, nasal PCT, and temporal PCT, respectively. There was an inverse relationship between temporal Dk/t and %ΔPCT ($p < 0.05$) while Dk/t was not found significantly associated with either CCT or nasal PCT. The patched eyes maintained a relatively stable CCT and showed progressive deswelling, starting and ending with 2.8% and 0.6%, respectively. In contrast, the unpatched eyes swelled, starting with nearly 0% and ending with 0.7% with a maximum swelling of 1.8%.

Conclusion: There was limited amount of corneal edema induced by short-term scleral lens wear with lens Dk/t ranging from 21 to 47 hBarrer/cm and lenses with lower lens Dk/t did not induce significantly higher corneal swelling. Scleral lens insertion soon after overnight eye closure with patching did not introduce additional swelling for young and healthy eyes.

1. Introduction

A scleral lens is a large diameter gas-permeable lens that rests on the sclera and creates a tear-filled vault over the cornea. Scleral lenses have been conventionally prescribed in treatment of various ocular surface diseases [1]. In recent years, the use of scleral lenses has increasingly become a preferred choice for correcting refractive errors, including irregular astigmatism [2]. However, thick post-lens tear film with scleral lenses can potentially create hypoxic effects, which may compromise ocular health (e.g., introducing corneal edema).

There have been four theoretical models in the literature for predicting corneal hypoxia with scleral lens wear. Michaud et al. [3] suggested lenses with oxygen permeability (Dk) over 150 Barrer, central lens thickness below 250 μm, and central post-lens tear thickness (PoLTT) below 200 μm to avoid hypoxia-induced swelling based on Fatt's method of combining oxygen transmissibilities (Dk/t) [4]. By predicting oxygen tension profile due to oxygen consumption and diffusion by following Chhabra et al.'s idea of utilizing Monod Kinetics [5], Compañ et al. suggested Dk over 125, central lens thickness below 200 μm, and PoLTT below 150 μm to avoid corneal swelling [6]. Using a different theoretical model, Jaynes et al. also drew similar conclusions, stating that only scleral lenses made from the highest Dk material and fitted without an excessive tear reservoir depth might avoid the corneal hypoxia [7]. Recently, Kim et al. [8] proposed a new theoretical model with considerations of metabolites, membrane resistance equations, and stromal thickness-hydration relations. They suggested that emphasis for preventing corneal hypoxia should focus on lens Dk/t rather than on PoLTT for lenses with Dk/t values less than 10. The

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https://doi.org/10.1016/j.clae.2019.04.002
Received 30 June 2018; Received in revised form 20 March 2019; Accepted 3 April 2019
1367-0484/

model suggested that within the practical ranges of lens Dk/t (e.g., 20 40 hBarrer/cm) and PoLTT (50–400 μm), the influence of lens Dk/t and PoLTT was minimal (e.g., no more than 1.5%). These results are consistent with several published clinical studies. Tan et al. [9] and Vincent et al. [10,11] reported that scleral lenses during short-term wear did not induce clinically significant central corneal edema. Tan et al. [9] and Lafosse et al. [12] also showed that variation of PoLTT did not lead to clinically significant difference in central corneal edema, suggesting that achieving a scleral lens fit with a low tear vault (e.g., < 200 μm) would not necessarily provide additional benefit to the corneal metabolic system. Lack of kinetics and transport of other metabolites that influence corneal swelling in the first three theoretical models may be the reason for the discrepancy between those models and existing *in vivo* studies [13]. Of interest, Pullum et al. have shown graphical presentations of an inverse relationship between corneal swelling and lens Dk/t values of sealed impression scleral lenses; however, it is not possible to draw definitive conclusions, as the authors did not provide statistical analysis [14–16].

Given the conflicting results reported from both model predictions and clinical studies in regard to the relationship between scleral lens Dk/t and corneal edema, it would be prudent to investigate corneal swelling under modern scleral lenses with a wide range of practical lens Dk/t values. In the present study, the effect of modern scleral lens Dk/t on corneal swelling was examined by utilizing cutting-edge technology such as high-resolution spectral domain optical coherence tomography (OCT) to assess *in vivo* changes in central and peripheral corneal thickness (CCT and PCT) and compared the clinical results to the values predicted by Kim et al.'s model. Additionally, the majority of contact lens wearers prefer to wear their lenses soon after waking up in the morning to obtain good vision, and scleral lens wearers are of no exception. Since the cornea swells during sleep and requires 1–2 hours after awakening to de-swell [17–19], it is unclear whether normal de-swelling pattern is different underneath a system that has a combination of thick contact lens and post-lens tear film. Thus, the effect of corneal thickness recovery from overnight eye closure with patching on the trend in CCT change was also evaluated during short-term scleral lens wear.

2. Methods

2.1. Study design

This was a prospective, double-masked, randomized, crossover, single-center (University of California, Berkeley, School of Optometry, Clinical Research Center) study. This research project, adhered to the tenets of the Declaration of Helsinki, was approved by an institutional review board (Committee for Protection of Human Subjects, University of California, Berkeley) and was compliant with the Health Insurance Portability and Accountability Act.

2.2. Subjects

Neophytes (no prior history of contact-lens wear or no contact-lens wear for at least one year prior to enrollment) were recruited from the University of California, Berkeley campus and the surrounding community. Eligibility criteria included age greater than 18 years old, a self-report eye examination within two years from the first study visit, spectacle spherical prescription between -0.25 and -8.00D, corrected visual acuity of 20/30 or better in each eye with habitual spectacles, and healthy ocular surface (i.e., free of ocular surface pathology, including moderate to severe dry eyes, and keratoconus).

2.3. Materials and procedures

This study was composed of four visits, with each scheduled on a separate day. At the first visit, subjects read and signed an informed consent, followed by baseline visual acuity assessments, screening evaluation of the ocular surface and scleral lens fitting. Based on corneal sagittal height, keratometry readings, and elevation maps generated by corneal topography (Medmont E300 Medmont International Pty Ltd, Vermont, Australia), subjects were fitted with trial lenses provided by Essilor USA to determine lens base curves for achieving optimal lens fit. All study lenses were mini-scleral lenses with 15.6 mm diameter and standard scleral lens design. To ensure no seal off during scleral lens wear, the peripheral lens edge landing was monitored to avoid impingement or compression of conjunctival blood vessels throughout the entire observational period. After 20–30 minutes of lens settling, over-refraction was performed to achieve the best corrected vision and PoLTT was measured using high-resolution spectral domain OCT (ENVSISU 2300, Bioptigen Inc, Durham NC). Once optimal lens parameters were determined, three pairs of mini-scleral lenses of 100, 140, and 160 Dk were ordered for each subject.

For visits 2-4, appointment times were scheduled in similar time blocks (± 30 min) with each subject arriving at least 2 h after awakening and with discontinuation of eye drops or allergy medications for one full day before the visit. Baseline visual acuity was measured and anterior ocular health was assessed with slit-lamp biomicroscopy (with white light only). Baseline CCT and PCT before lens insertion were measured. Subjects were instructed to look straight ahead at the OCT light source, while the corneal apex was centered in both horizontal and vertical preview windows. When the corneal apex was centered, a completely modulated white band appeared at the center presenting full brightness saturation. To image central cornea, a radial scan (100 frames per scan) was acquired with the corneal apex being centered. To image peripheral (nasal and temporal) cornea, after ensuring the eye was centered, subjects were asked to look at peripheral fixation targets. Once the region of interest was located, a linear scan (8 mm long, 30 B-scans per linear scan, 1000 A-scans per B scan) was acquired. After baseline CCT and PCT measurements, one of three pairs of scleral lenses (100, 140, and 160 Dk) with the same base curve was inserted by the investigator, according to a pre-determined randomization scheme. After lenses were inserted and allowed to settle for about 20 min, the lens surfaces and fit were evaluated by the investigator, and then subjective comfort was reported. CCT measurements were obtained immediately after lens insertion, and after 10 min, 20 min, 30 min, 60 min, 1.5 h, 2 h, 3 h, 4 h, and 5 h of lens wear. Immediately after lens removal at the end of the 5 h period, peripheral cornea was imaged again using OCT.

All the corneal thickness image analysis was performed by the same observer to eliminate inter-observer variability. Before performing thickness assessments on OCT images, every frame of the radial scan of the central cornea was examined to find a frame with the white band as a line of symmetry of both scleral lens and corneal surfaces. This frame and the frames with the same frame number in the subsequent radial scans for 5 h would be used for CCT, PoLTT, and lens thickness quantifications. A caliper tool provided by Bioptigen software was used to measure CCT at the corneal apex located by the white band. The Dk/t value, referring to oxygen transmissibility at the center of a scleral lens, was calculated using central lens thickness measured by the same caliper tool along the same meridian during CCT measurement. The repeatability of CCT assessment has been examined and published [17]. Because of geometric and refractive image distortions in OCT imaging [20–22], it was impossible to perform PCT assessment using the same method as CCT measurement. Thus, to measure PCT changes, baseline and immediately-after-lens-removal OCT images of the peripheral cornea were automatically transposed into one image with a script written in MATLAB R2016b (Mathworks, Natick, MA) (Fig. 1). Then five evenly spaced reference points were chosen within a 100pixel-range (1 pixel = 8.000 μm horizontal) region of interest, selected by the observer, to determine the average thickness change at the peripheral cornea. Thickness change was measured based on vertical pixel count of the image. The vertical pixel count was converted into μm based on the

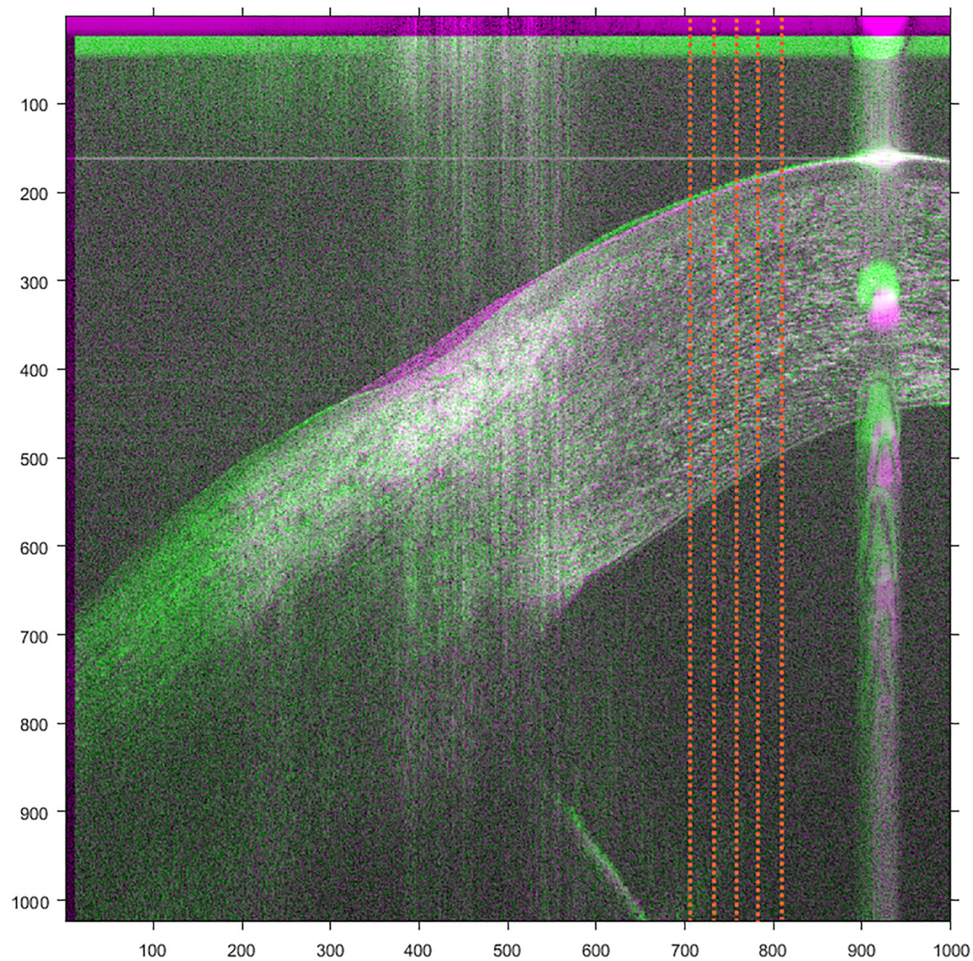

Fig. 1. Transposed OCT image of PCT change (Purple color is before lens insertion, green is after lens removal. Orange lines are the points where the swelling was measured.).

instrument vertical image resolution (1 pixel = 3.125 μm vertical). The repeatability of PCT measurement was tested. The test was based on three randomly selected OCT images, with which the same observer twice measured the PCT at temporal and nasal quadrants. The observer was masked without knowing the values of the prior measurements. Bland-Altman method was used to calculate the mean and standard deviation of the difference between each pair-measurement and derive Limits of Agreement (LoA) plot.

To investigate the effect of the time lapse between awakening and lens insertion on corneal edema, four subjects were randomly selected for one additional visit with Dk 100 Barrer scleral lenses. These four subjects reported to the Clinical Research Center at least one day before the additional visit for patching instructions (i.e., patching a randomized eye using medical tape and an eye pad before night sleeping). On the next day, VA, ocular surface assessment, and CCT measurements were performed on the unpatched eye first so that the eye under the patch could remain closed for as long as possible without full recovery from corneal swelling caused by overnight eye closure with patching. Immediately after patch removal, CCT of the previously patched eye was measured, followed by baseline visual acuity and anterior ocular health assessments with white light only. Thereafter, both lenses were inserted and CCT measurements over 5 h of lens wear were performed for both eyes.

2.4. Statistical analysis

A major concern inherent to a multi-period, cross-over study is the lack of independence in the data obtained from the same subject. Ignoring the correlation would reduce p-values. Therefore, a mixed-effect model was used to address this issue. Variables of interest, such as Dk/t, and PoLTT, were analyzed as fixed-effect terms. The correlation between outcomes from repeated measurements and paired-eyes of each subject was assigned as random-effect. The analysis method was applied by using PROC MIXED procedure with RANDOM statement in SAS9.2®.

3. Results

3.1. Subject demographics and lens parameters

Ten neophytes (6 females; 4 Asians, 3 Caucasians, 1 Hispanic, and 2 other ethnicities; mean [95% CI] age of 22.2 [20.6, 23.8] years) with healthy ocular surface completed the study. Table 1 reports average values of the study lens parameters. All lenses were ordered with

Table 1
Lens parameters.

Variable	Mean	Std Dev	Min	Max
Base curve	7.76	0.38	7.18	8.23
Lens power	−3.93	2.53	−7.00	0.00
Lens thickness*	421.35	54.47	332.90	511.40

* To minimize measurement error, the central thickness of each lens was obtained by averaging 10 measurements taken from immediately after lens insertion, and after 10 min, 20 min, 30 min, 60 min, 1.5 h, 2 h, 3 h, 4 h, and 5 h of lens wear.

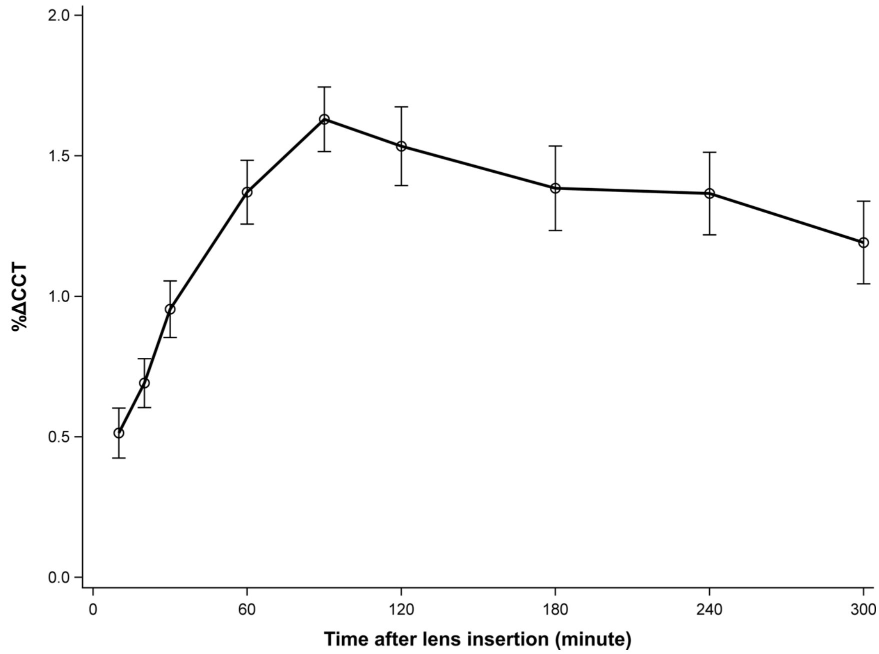

Fig. 2. Percentage change in CCT(%ΔCCT) during 5-hour lens wear period.

standard spherical peripheral curves.

3.2. Central corneal thickness

CCT increased during the first 90 min, reaching a plateau thereafter, as shown in Fig. 2. Mean [95% CI] CCT immediately upon lens insertion (baseline) was 532.4 [520.3, 544.5] μm. At the end of 5 h, CCT increased to 538.7 [526.5, 551.0] μm, which was significantly higher than the baseline ($p < 0.001$). Mean [95% CI] central corneal edema at the end of 5 h was 1.2% [0.9%, 1.5%]. Table 2 lists the percentage change of CCT (%ΔCCT) from the baseline after lens insertion at each time point. A maximum central corneal edema of 1.6% [1.4%, 1.9%] was observed at 1.5 h. As shown in Table 3, PoLTT of 10 subjects had a narrow range throughout the entire lens-wear period, especially after lens settling. There was no significant relationship between %ΔCCT and PoLTT ($p = 0.80$). Thus, PoLTT was not included in the analysis for examining the effect of Dk/t on %ΔCCT.

3.3. Effect of oxygen transmissibility on CCT and PCT

Mean [95% CI] Dk/t of all study lenses was 32.0 [29.2, 34.7] hBarrer/cm, ranging from 21 to 47 hBarrer/cm. There was no significant relationship ($p = 0.46$) between central corneal edema and Dk/t, and the difference in %ΔCCT between maximum and minimum Dk/t was less than 0.5% (Fig. 3). There was no significant relationship between the maximum central corneal edema observed at 1.5 h and Dk/t ($p = 0.75$).

Table 2
%ΔCCT during 5-hour lens wear period.

Time (minute)	Mean [95% CI]	Min	Max
10	0.5 [0.3,0.7]	−0.9	1.4
20	0.7 [0.5,0.9]	−0.9	1.5
30	1.0 [0.7,1.2]	−0.4	2.1
60	1.4 [1.1,1.6]	−0.5	3.0
90	1.6 [1.4,1.9]	0.7	3.5
120	1.5 [1.2,1.8]	0.0	3.7
180	1.4 [1.1,1.7]	0.2	3.5
240	1.4 [1.1,1.7]	−0.2	3.2
300	1.2 [0.9,1.5]	−0.7	2.9

Table 3
PoLTT at each time point.

Time (minute)	Mean	Std Dev	Minimum	Maximum
0	254	50	145	345
10	235	38	147	307
20	228	33	151	284
30	222	36	107	276
60	210	35	117	257
90	198	33	106	252
120	195	33	115	245
180	189	31	115	254
240	181	31	98	227
300	180	33	102	262

LoA of PCT measurement was evaluated. The mean difference of two repeated measurements was 0.058% with 95% CI [-0.254%, 0.371%]. All repeated data were within 95%LoA, implying a good repeatability. Mean [95% CI] %ΔPCT was 1.2% [0.87, 1.44] nasally and 0.8% [0.57, 1.08] temporally (Table 4). There was no significant difference in %ΔPCT between nasal and temporal ($p = 0.49$) but an inverse relationship between %ΔPCT and Dk/t in the range of 21–47 hBarrer/cm was observed in the temporal peripheral cornea only ($p = 0.03$) (Fig. 4).

3.4. Effect of corneal thickness recovery after overnight eye closure with patching on CCT

A consistent pattern was observed among the subjects who wore patches — the initial CCT for the patched eye immediately after patch removal was greater than for the unpatched eye by ˜20 μm and the difference decreased to ˜5 μm at the end of 5 h lens wear. Fig. 5 presents %ΔCCT in the patched and unpatched eyes, using these subjects' baseline CCT obtained from different days when the corneas had fully recovered from overnight corneal swelling. During 5 h lens wear, the patched eyes maintained a relatively stable CCT and showed progressive deswelling (˜1%). In contrast, the unpatched eyes started swelling and reached a plateau around 90-min post lens insertion. The values of %ΔCCT for the patched and unpatched eyes reached the same level at around 3 h after lens insertion.

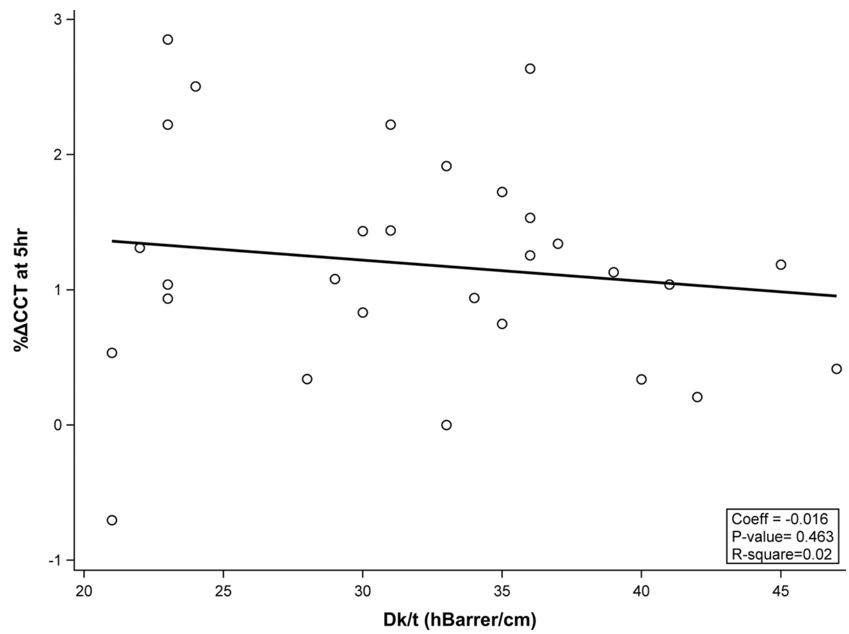

Fig. 3. Scatter plot with regression line on %ΔCCT with respect to Dk/t of scleral lenses.

Table 4
Peripheral %ΔCT from baseline and immediately after lens removal.

Location	N	Mean	Std Dev	Min	Max	P-value
Nasal	28	1.15	0.73	−0.12	2.59	0.817
Temporal	30	0.82	0.69	−0.54	2.57	0.526

4. Discussion

As scleral lenses have increasingly become the preferred choice in recent years for correcting irregular cornea and treating ocular surface diseases [1,2,23,24], they have provoked concerns about potentially undesirable clinical events due to lens-induced hypoxia [2,3,8,11]. Different mathematical models suggest that scleral lenses with the highest Dk materials and without excessive tear reservoir should be required to avoid hypoxic corneal events [3,6,7,25]. However, there is no definitive evidence to support clinically significant events when scleral lenses are fitted otherwise for young and healthy eyes. In this study, scleral lenses worn by young and healthy subjects induced about 1.2% central corneal edema at the end of 5 h lens wear, which was smaller than physiological corneal swelling after overnight eye closure (˜3.6%) [17]. To date, there is no data available to estimate the potential impact of such chronic and low hypoxic stress from scleral lens wear. Although an inverse relationship between %ΔCCT and lens Dk/t

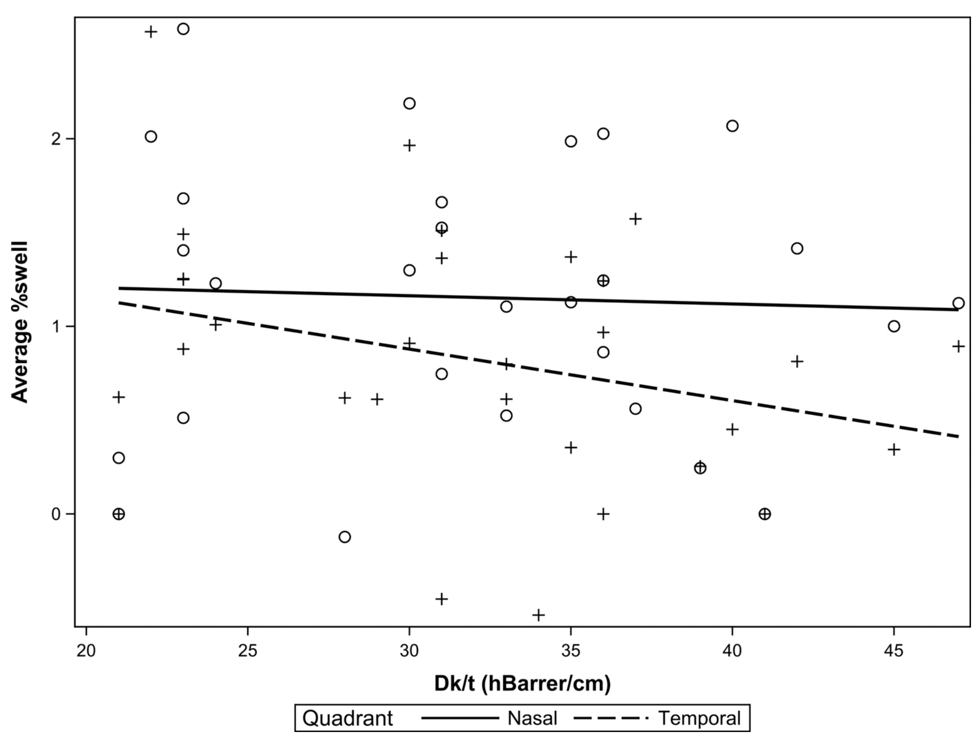

Fig. 4. Peripheral %ΔCT at 5 hs vs. Dk/t.

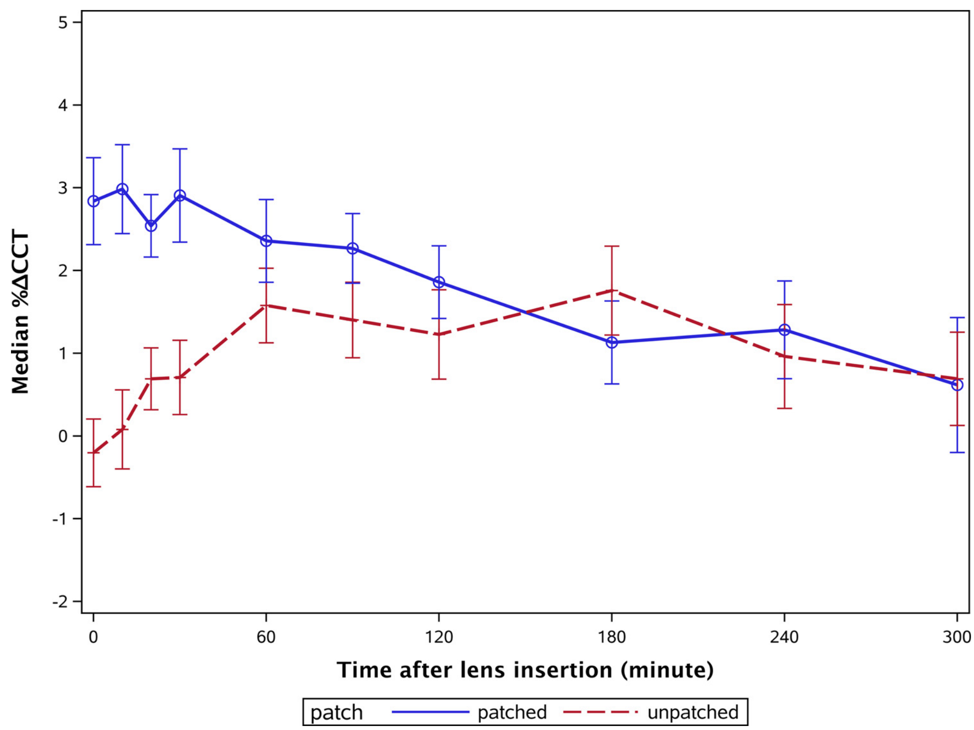

Fig. 5. %ΔCCT of four subjects with patched eyes. It presented the CCT change of patched and unpatched eyes in percentage, using the subjects' baseline CCT obtained from different days when the subjects' cornea had fully recovered from overnight corneal swelling.

was found in the range of 21–47 hBarrer/cm, this trend was not statistically significant. It is important to note that the reported Dk/t values may not be a good representative for the entire scleral lens oxygen transmissibility because it was calculated based on its corresponding central lens thickness. Vincent et al. [26] recommended that an average lens thickness value derived from the entire lens profile should be used for the calculation of lens Dk/t.

In the present study, PoLTT showed minimal impact on corneal swelling on young and healthy eyes with lens Dk/t of 21–47hBarrer/cm. This finding is in agreement with some published clinical data [27,28], but in disagreement with others [29,30]. Both Compan et al. [29] and Gissson et al. [30] drew their conclusions based on either theoretical predictions or measurements of oxygen partial pressure across the cornea behind scleral lenses. However, oxygen partial pressure is not a direct measurement of corneal edema. Compan et al. also measured corneal edema with different sagittal depths in attempt to create various PoLTT. Unfortunately, their results were inconclusive regarding the relationship between PoLTT and corneal swelling due to study limitations, including that Dk/t values of the study lenses were not accounted for and PoLTT measurements were not obtained.

The difference in %ΔCCT between the patched and unpatched eyes among the four subjects agreed with what was found regarding the rate of corneal deswelling [17] — the unpatched eye recovered by approximately 3˜4% at 140–150 minutes post awakening. The patched eyes, which were not allowed for corneal deswelling from overnight eye closure, continued to deswell during lens wear and eventually presented a similar %ΔCCT compared with the unpatched eyes after approximately 3 h of lens wear. This preliminary result indicates that recovery time given to a swollen cornea from overnight eye closure with patching before scleral lens insertion does not affect corneal edema after 3 h lens wear for young and healthy eyes. Further investigation with a sufficient sample size comparing normal with compromised corneas is warranted to provide more understanding about the effect of recovery time from overnight eye closure on corneal thickness change during scleral-lens wear. Such a comparison would be especially important for compromised corneas to determine whether it is safe to insert scleral lenses soon after awakening.

It is important to note that a true peripheral corneal thickness measurement is defined as the distance between the most outer and inner layers of the cornea along a perpendicular line to the anterior ocular surface. OCT axial direction is the same as the perpendicular direction only at the central corneal region. At the other locations, deviating from the central cornea, axial and perpendicular directions will not be parallel and superimposed. Instead, an angle will be present between the two directions. Therefore, the PCT measurements reported in the present study were based on the distances between two layers along the OCT axial direction. However, since only percentage change of thickness along OCT axial direction was reported, the result in the present study should be equivalent to the relative percentage change of the true PCT along the perpendicular direction. After 5 h lens wear, there was limited peripheral corneal edema found temporally and nasally with no significant difference between regions ($p > 0.05$). While the nasal peripheral corneal swelling was independent of lens Dk/t in the range of 21–47 hBarrer/cm, a lower lens Dk/t value was found to be significantly associated with a higher temporal relative corneal swelling. Sampling variability could be a reason for these findings; nevertheless, further investigation is warranted.

In conclusion, modern scleral lenses with various Dk/t (21–47 hbarrer/cm) during short-term wear induced limited amounts of corneal swelling and lenses with lower lens Dk/t did not induce significantly higher corneal swelling.

Taxonomy

Scleral Contact Lens; Contact Lens Manufacture.

Grant/financial support

Clinical Research Center Unrestricted Fund (MC Lin); Lagado Corporation for donating lens materials; Essilor USA for research fund (MC Lin).

Commercial relationship interest

None.

References

[1] J.H. Kok, R. Visser, Treatment of ocular surface disorders and dry eyes with high gas-permeable scleral lenses, Cornea 11 (November (6)) (1992) 518–522.
[2] E. van der Worp, A guide to scleral lens fitting, Available from: 2 ed., Scleral Lens Education Society, 2015, https://commons.pacificu.edu/mono/10/.
[3] L. Michaud, E. van der Worp, D. Brazeau, R. Warde, C.J. Giasson, Predicting estimates of oxygen transmissibility for scleral lenses, Cont Lens Anterior Eye 35 (December (6)) (2012) 266–271.
[4] I. Fatt, Oxygen transmissibility considerations for a hard-soft contact lens combination, Am J Optom Physiol Opt 54 (October (10)) (1977) 666–672.
[5] M. Chhabra, J.M. Prausnitz, C.J. Radke, Modeling corneal metabolism and oxygen transport during contact lens wear, Optom Vis Sci 86 (May (5)) (2009) 454–466.
[6] V. Compañ, C. Oliveira, M. Aguilella-Arzo, S. Mollá, S.C. Peixoto-de-Matos, J.M. González-Méijome, Oxygen diffusion and edema with modern scleral rigid gas permeable contact lenses, Invest Ophthalmol Vis Sci 55 (September (10)) (2014) 6421–6429.
[7] J.M. Jaynes, T.B. Edrington, B.A. Weissman, Predicting scleral gp lens entrapped tear layer oxygen tensions, Cont Lens Anterior Eye 38 (February (1)) (2015) 44–47.
[8] Y.H. Kim, B. Tan, M.C. Lin, C.J. Radke, Central corneal edema with scleral-lens wear, Curr Eye Res 43 (November (11)) (2018) 1305–1315.
[9] B. Tan, Y. Zhou, T.L. Yuen, K. Lin, L. Michaud, M.C. Lin, Effects of scleral-lens clearance on corneal edema and post-lens tear dynamics: a pilot study, Optom Vis Sci 95 (June (6)) (2018) 481–490.
[10] S.J. Vincent, D. Alonso-Caneiro, M.J. Collins, Corneal changes following short-term miniscleral contact lens wear, Cont Lens Anterior Eye 37 (December (6)) (2014) 461–468.
[11] S.J. Vincent, D. Alonso-Caneiro, M.J. Collins, A. Beanland, L. Lam, C.C. Lim, et al., Hypoxic corneal changes following eight hours of scleral contact lens wear, Optom Vis Sci 93 (March (3)) (2016) 293–299.
[12] E. Lafosse, D.M. Romín, J.J. Esteve-Taboada, J.S. Wolffsohn, C. Talens-Estarelles, S. García-Lázaro, Comparison of the influence of corneo-scleral and scleral lenses on ocular surface and tear film metrics in a presbyopic population, Cont Lens Anterior Eye 41 (February (1)) (2018) 122–127.
[13] B.K. Leung, J.A. Bonanno, C.J. Radke, Oxygen-deficient metabolism and corneal edema, Prog Retin Eye Res 30 (November (6)) (2011) 471–492.
[14] K.W. Pullum, F.J. Stapleton, Scleral lens induced corneal swelling: what is the effect of varying dk and lens thickness? CLAO J 23 (October (4)) (1997) 259–263.
[15] K.W. Pullum, A.J. Hobley, J.H. Parker, Hypoxic corneal changes following sealed gas permeable impression scleral lens wear, J Brit Contact Lens Assoc 13 (1990) 83–87.
[16] K.W. Pullum, A.J. Hobley, C. Davison, 100+ dk: does thickness make much difference? J Br Contact Lens Assoc 14 (1) (1991) 17–19.
[17] J. Niimi, B. Tan, J. Chang, Y. Zhou, A. Ghanekar, M. Wong, et al., Diurnal pattern of tear osmolarity and its relationship to corneal thickness and deswelling, Cornea 32 (October) (2013) 1305–1310.
[18] S.A. Read, M.J. Collins, Diurnal variation of corneal shape and thickness, Optom Vis Sci 86 (March (3)) (2009) 170–180.
[19] M.J. Giráldez-Fernández, A. Díaz-Rey, C. García-Resua, E. Yebra-Pimentel-Vilar, Diurnal variations of central and paracentral corneal thickness and curvature [in Spanish], Arch Soc Esp Oftalmol 83 (March (3)) (2008) 183–191.
[20] S. Ortiz, D. Siedlecki, I. Grulkowski, L. Remon, D. Pascual, M. Wojtkowski, et al., Optical distortion correction in optical coherence tomography for quantitative ocular anterior segment by three-dimensional imaging, Opt Express 18 (February (3)) (2010) 2782–2796.
[21] A. Podoleanu, I. Charalambous, L. Plesea, A. Dogariu, R. Rosen, Correction of distortions in optical coherence tomography imaging of the eye, Phys Med Biol 49 (April (7)) (2004) 1277–1294.
[22] V. Westphal, A. Rollins, S. Radhakrishnan, J. Izatt, Correction of geometric and refractive image distortions in optical coherence tomography applying Fermat's principle, Opt Express 10 (May (9)) (2002) 397–404.
[23] D. Ozek, O.E. Kemer, P. Altiaylik, Visual performance of scleral lenses and their impact on quality of life in patients with irregular corneas, Arq Bras Oftalmol 81 (Nov./Dec. (6)) (2018) 475–480.
[24] H.S. Chu, I.J. Wang, G.A. Tseng, W.L. Chen, Y.C. Hou, F.R. Hu, Mini-scleral lenses for correction of refractive errors after radial keratotomy, Eye Contact Lens 44 (November Suppl 2) (2018) S164–8.
[25] B.A. Weissman, P. Ye, Calculated tear oxygen tension under contact lenses offering Resistance in series: piggyback and scleral lenses, Cont Lens Anterior Eye 29 (December (5)) (2006) 231–237.
[26] S.J. Vincent, D. Alonso-Caneiro, H. Kricancic, M.J. Collins, Scleral lens thickness profiles: the relationship between average and centre lens thickness, Cont Lens Anterior Eye 16 (March) (2018) [Epub ahead of print].
[27] F. Esen, E. Toker, Influence of apical clearance on mini-scleral lens settling, clinical performance, and corneal thickness changes, Eye Contact Lens 43 (July (4)) (2017) 230–235.
[28] S.J. Vincent, D. Alonso-Caneiro, M.J. Collins, The time course and nature of corneal oedema during sealed miniscleral contact lens wear, Cont Lens Anterior Eye 13 (March) (2018) [Epub ahead of print].
[29] V. Compañ, C. Oliveira, M. Aguilella-Arzo, S. Mollá, S.C. Peixoto-de-Matos, J.M. González-Méijome, Oxygen diffusion and edema with modern scleral rigid gas permeable contact lenses, Investig Ophthalmol Vis Sci 55 (September (10)) (2014) 6421–6429.
[30] C.J. Giasson, J. Morency, M. Melillo, L. Michaud, Oxygen tension beneath scleral lenses of different clearances, Optom Vis Sci 94 (April (4)) (2017) 466–475.